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# Research and development aspects of pico-hydro power

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ABSTRACT

Intensive explorations of different alternatives and renewable energy resources are currently being conducted worldwide. Pico-hydro power is at the forefront of these options because it is considered as the most cost-effective renewable energy option to provide electricity for rural areas, and to enable energy to be derived from extremely low head and flow streams of 1 m and 1 L/s, respectively. This review discusses the research and development aspects of pico-hydro and the factors influencing the success of the pico-hydro scheme in rural areas. These factors are also likely to increase the demand for pico in a rural energy market. This paper concurs with the view held by many researchers and experts that customs duty imposed on pico-hydro components is a major obstacle to the dissemination of renewable energy because it raises original cost by up to 40%. The future of the pico-hydro market looks prosperous because there is substantial availability of low head and flow hydroelectric sites in less developed countries. In the future, technology can play a crucial role in the lighting of houses in remote communities, with the energy source derived from domestic water supply.



**Contents**



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## 1. Introduction

Pico-hydro refers to the smallest scale in a hydropower plant [1–6] with a capacity of less than 5 kW [2,3,5–12]. In some countries, pico-hydro is also known as family hydro because it can be owned by a single household [2,4,6,12]. In fact, it is quite similar to other scales, though it is only a thumbnail image of the large scales [7]. However, large-scale sizes are becoming smaller and modifications have been made to make the generating unit more compatible with different site characteristics.

In the energy crisis era, the number of people who do not have access to electricity accounts for 1.6 billion in rural areas [13]. This number will be multiplied by at least 1 in the future unless a cost-effective solution is adapted, particularly for less developed countries. Solutions such as a pico-hydro turbine is becoming an attractive prospect in satisfying the basic electricity needs of remote communities [1].

## 2. Research and development

Although pico-hydro technology for low head application has only been drawing attention from researchers and policymakers in the recent past, it is not a new technology but rather a mature technology parallel to other hydro scales [14–16]. In many parts of the world, various types of pico-hydro technology have been in use for some 30 years [2,15,17–21], mostly for the rural electrification in developing countries, particularly in China and other countries in the area [2,15,17–21]. However, increasing demand for electricity [22], low level of electrification in remote areas [23], rural development and poverty alleviation programs, global warming [23], era of advanced technology, and publicity of pico in developing countries [15,23] have caused researchers and policymakers to rethink and refocus on the research and development (R&D) of pico-hydro turbines. The increased interest is due to the potential and capability of pico-hydro turbines to be alternative and ideal solutions to increase the demand for electrification in remote communities [24].

R&D work has focused on two aspects of the pico-hydro turbine to improve the affordability for low-income households and to reduce maintainability and serviceability of the unit, namely, cost-effectiveness and universal design for local manufacturability [25,26]. Academic and renewable energy research institutes, government/private sectors, and nonprofit organizations are the main promoters, sponsors, shareholders, and funders of R&D in the pico-hydro scale. They cooperate in order to develop durable, low-cost, and more efficient turbines [27] based on the design requirements of remote areas. These turbines are usually coupled with induction generators [14,27,28] and electronic load controllers (ELC) to achieve a complete package [27] for quality, reliability, and safety.

### 2.1. Motivations for R&D in pico-hydro turbines

Several motivations and incentives drive researchers to conduct R&D in pico-hydro turbines. The main motivational drivers are presented below.

- Large expected pico-hydro global market size in developing countries [2,15,17,21].
- High cost of grid connection in remote areas [29] and unreliable power supply from national electricity grids [30].
- Site availability for low head. Given the sufficient number of low head sites in many countries around the world, these sites can offer significant sources of distributed power [31] without the need for grids even in developed countries as a shift toward sustainable energy.
- Growing demand for more efficient and reliable turbines with high output and long lifespan [6,17,27] to overcome the most frequent failures of other poor-quality units available in the pico-hydro market. These designs are highly adaptable to suit the harsh environments of remote areas [6,17,27].
- Environmental legislation such as the Clean Development Mechanism (CDM), which is a perfect mechanism for rapid stimulation of the pico-hydro market in developing countries, where the cost of pico-hydro can be lowered and foreign investment in renewable energy can be obtained and ensured [17,32].
- To best-fit the minimum energy requirement of remote villages for electrification [24].
- To improve the living standards and to generate income for low-income households [2,5,29].

### 2.2. Types of pico-hydro turbines and their development

Pico-turbines work under the same principle as other hydropower turbines and applies the same hydro power equation [32]:

$$P = \eta_t \rho_w g Q h_{\mathrm{eff}} \tag{1}$$

where $P$ is the mechanical power produced at the turbine shaft (watts), $\eta_t$ is the hydraulic efficiency of the turbine (%), $\rho_w$ is the density of water (kg/m$^3$), $g$ is the acceleration due to gravity ($g$=9.81 m/s$^2$), $Q$ is the volume flow rate passing through the turbine (m$^3$/s), and $h_{\mathrm{eff}}$ is the effective pressure head of water across the turbine (m).

Pico-hydro is believed to have been first used in South China in the late 1980s, with surrounding countries soon following [2,15,17–21]. The adoption of pico-hydro by these countries is due to the ability of pico-turbines to derive energy from even very low head and flow streams at 1 m and 1 L/s, respectively [2,6,14]. Sites that are less than 5 m were found to be the most usable head for pico-turbines because the ramifications of rivers, streams, waterfalls, and irrigation channels are abundant in nature [2,6,14,33–38].

Different pico-hydro turbine designs in the low head scale have been developed and spread to several countries to meet the growing demand for rural electrification in remote communities [15,24,39]. Each type of pico-hydro turbine is distinguishable according to the principle of work, the civil works needed, and the range of power generated [15]. Several varieties of turbines available in the low head range may be found and used in rural areas for rural electrification, including Peltric set, low-cost DC pico-hydro system, and pico power pack (PPP), etc.

*Peltric set.* Peltric is an abbreviation for Pelton+Electric [40]. It was developed in Nepal in 1991 [41] for sites with 20–50 m head

to generate electricity and only requires a hose-pipe for a penstock [6]. Peltric is a small (can be 60 W), simple, and standalone pelton turbine with a vertical shaft coupled directly to the induction generator; it is easy to install, operate, and maintain, and is affordable to most low-income households [42].

*Low-cost DC pico-hydro system*. This system is composed of a small Pelton wheel with a horizontal shaft coupled to a 12 V DC vehicle alternator by a pulley belt working as a generator. It was developed at Fundacion Desarollo de Technologias Appropriadas in Colombia, South America. The main features of this design are [24] that it is simple and easy to manufacture locally and the 12 V DC car or truck alternator as a generator comes with a voltage regulator. Thus, money is saved by avoiding the need to pay for a new control system. The system can also provide mechanical power for other usages.

*Pico power pack*. The PPP is a combination of the above two turbines [24], where a Pelton runner is connected directly to an induction generator situated horizontally with an extended shaft (which can drive farming equipment throughout the daytime to improve the financial viability of the projects). It was developed at the end of the 20th century at The Nottingham Trent University with the help of a German exchange student, Lutz Homeier, and was tested in the village of Kushadevi, Nepal [37]. This type of turbine is easily accessed for inspection and maintenance, and is equipped with capacitors and ELC for AC generation and voltage regulation. Moreover, this design takes advantage of the two turbines by, for example, using the same induction motor with the Peltric Set to enable the turbine to generate AC, which means that the electricity can be shared economically up to 1 km away from the powerhouse [24].

The flow rate and head needed for PPP are usually 3–15 L/s and 25–100 m, respectively [37].

*Motor Dynamo Based Family Hydro* (*MDFH*). MDFH is also known as the Hydro Home System (HHS) [23]. This configuration was developed around 2007 by the Centre for Rural Technology, Nepal (CRT/N) with the support of the Lemelson Foundation (USA) and Katmandu University [23,43]. The configuration involved a tiny Pelton runner coupled with a 12 V car dynamo to generate electricity ranging from 60 to 100 W from a head of 20–30 m with a flow rate of 1–2 lps. The parameters of these turbines, including water flow and head, can be obtained from the domestic water supply [23,43]. The power generated by MDFH is adequate in meeting the electricity demand of a household in mountain areas [23].

*Stream engine*. This is a small pelton wheel with a vertical shaft, a generator situated on top, and the control box located in front (Fig. 1). It was developed in Canada for low-power turbines and for higher head and very low flows [44].

*Turgo turbine*. This type of turbine is preferred for medium head sites because it has the added advantage of being able to handle high head sites [6]. It comes with different designs and is pervasive throughout the world, even in developed countries such as Australia, Canada, and the USA [6]. Fig. 2 shows a small and cheap Vietnamese 200 W pico-hydro "turgo" unit for medium head installations and used in remote areas such as in Ecuador [33].

*PowerPal*. PowerPal is an improved copy of the MTD series [33] developed in Hanoi, Vietnam, by a Canadian firm, Asian Phoenix Resources Ltd., for use in small hydropower sites (high and low head). It can generate power ranging from 200 W upwards (20 kW) [45]. The low head PowerPal 200, 500, and 1000 W pico-turbines (Fig. 3) are widely used in less developed countries and are now sold in over 60 countries [45], even in developed countries such as the UK for electricity generation [44]. It is suitable for 1–2 m head [6].

The PowerPal components and working principle are shown in Fig. 4, where the generator is a simple AC single-phase, brushless

**Fig. 1.** Peltric set installed in a developing country [24].


**Fig. 2.** Pelton runner and extended shaft on PPP [37].

permanent magnet alternator attached to a propeller turbine [45]. As the water enters from the top and flows through the draft tube, it forms a vortex which creates a suction causing the propeller to rotate [45]. PowerPal is lightweight and portable, thus requiring only minimum civil works. It is also simple and easy to install with low maintenance costs and no running costs. Furthermore, the manufacturer has provided PowerPal with an ELC to avoid voltage fluctuation [44,45].

*Open-flume turbines*. This turbine, which is an improvement on the PowerPal low head turbine, was developed in Indonesia by CihanjuangInti Teknik as a standardized package for heads below 6 m. It is equipped with a manual flow control mechanism, which makes it easy to install and maintain [12]. The turbine shown in Fig. 5 illustrates a typical example of turbine modification for performance improvement.

*Axial and cross flow turbine*. Although this turbine has the advantage of being easy to manufacture locally [14], the axial and

**Fig. 3.** Installed PPP [24].

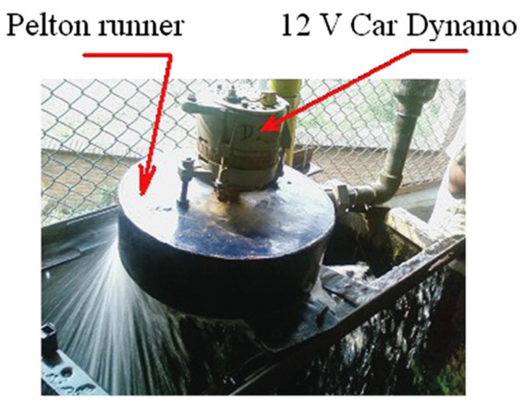


**Fig. 4.** The HHS [23].

**Fig. 5.** Stream engine [44].

cross flow turbine has been used only in a few less developed countries. For instance, small cross flow turbines have been used in Colombia, the Philippines (known as ''Fireflies'') and Nepal (known as ''Crosstric Set'') for 5–20 m heads and a flow range of 5–50 L/s [2,6,27]. The huge size and slow rotation speed [14] of axial and cross flow turbines are the reasons many countries avoid using them (Figs. 6–11).

*Submersible pico-hydro turbine*. This turbine is also known as the submersible, underwater 100, instream [47], or Jack Rabbit [48] pico-hydro turbine. It was developed by [47] to power ocean or river scientific instruments for marine oil exploration expeditions, study of aquatic life, or to recharge batteries for yachts [47,48]. This turbine can be suitable for remote areas because it extracts energy from any 400 mm deep fast flowing stream without the need for head [47] or massive flow rate (which is abundant in those areas). The UW 100 is a rugged, permanent magnet, low-speed, high-output alternator sealed in an oil-filled waterproof housing with a maximum power rating of 100 W at 4 m/s and is able to generate up to 2.4 kW h per day, which is sufficient to supply electricity for a typical remote home [47–49]. As this system is a submersible turbine, there is no risk during floods, no power house is needed above the turbine, and the unsightly visual and unfavorable noise impacts of the scheme are significantly reduced. A low price can also be achieved if it is manufactured locally in developing countries [47,49].

*Pumps as turbines* (*PAT*). PAT is not a new concept as it has been recognized by pump manufacturers and used for a long time now [50]. However, [51] traced the initial use of PAT and found that pumps were not specifically tested for use as turbines, but rather, generally referred to in the study by Thoma and Kittredge, who, in 1931, incidentally found that pumps can work efficiently in reverse directions as turbines during their testing of pumps to determine pump characteristics. Nowadays, guidelines for the selection of PAT are available [52], and pumps running in reverse mode are widely used [51], proving to be a suitable and attractive option for low head hydropower generation in remote areas [14,51,53,54]. This situation is especially true in places where pico-hydro turbines are insufficient and unaffordable [50,53]. Pumps have two main usages in the field of electricity production.

**Fig. 6.** Vietnamese 200 W medium head pico-hydro ''turgo'' unit in Ecuador [33].

First, pumps can be used during low electric power demand to store energy in the form of head and when power is needed it can be used as a turbine to generate electricity [51]. Second, pumps can be used as energy-recovery devices for cases such as water supply networks and the chemical industry [50,51].


**Fig. 7.** PowerPal [44].

Low-income households in remote areas appreciate pumps over custom-made turbines for the following advantages:

- PAT is a 2-in-1 technology that incorporates the turbine runner and generator as a set, and is available for a wide range of heads and flows [55].
- They are considered as less complicated than turbines [50,51] because they only require simple technology to fabricate [54]. This feature makes them easy and cheap to design, install, operate, and maintain, with the additional advantage that all of these can be done locally [53–55]. Therefore, they have become standardized products and can be produced in bulk [51], making them easily available in most less developed countries [14,53,54] with the inclusion of their spare parts such as seals and bearings [55].
- They have low maintenance cost compared with turbines [51] because their bearing has a long life span [55].
- They can produce additional mechanical power from the other end of the generator to drive farming equipment [3].
- They have been successfully proven and used for low head hydro in some less developed countries such as Thailand and Kenya [25,56].

The 200–1000 W pico-hydro turbines are the most common units in the marketplace, and are particularly popular in rural

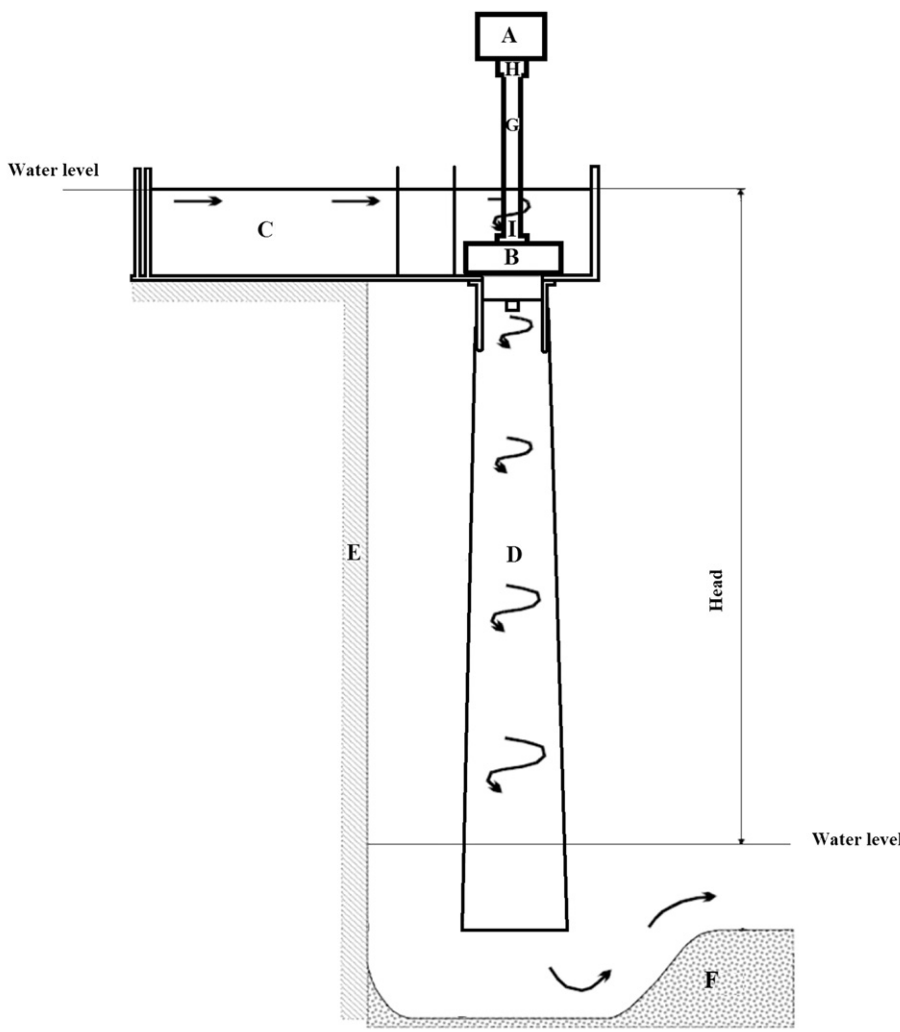


**Fig. 8.** PowerPal components [45].

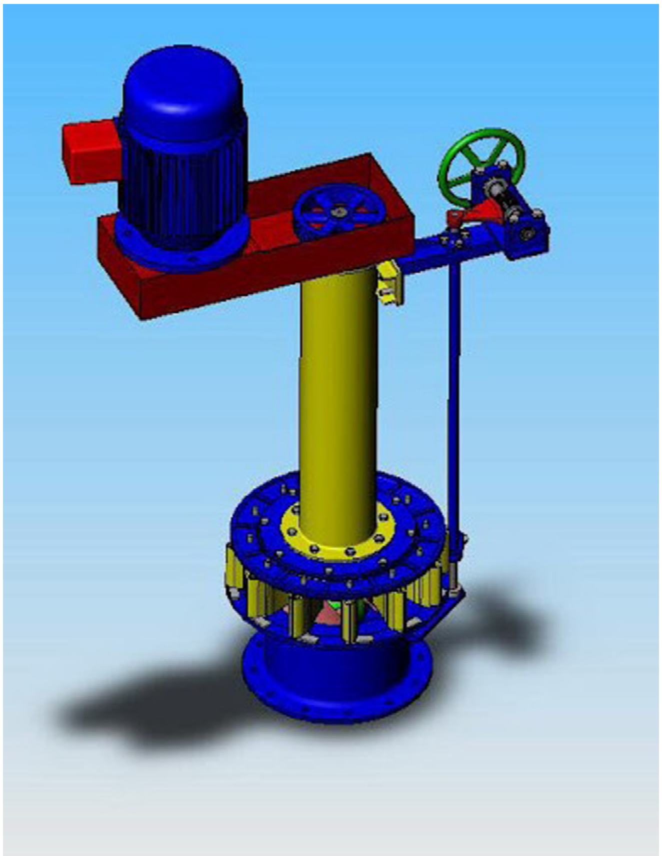

**Fig. 9.** Open-Flume Turbines made in Indonesia [46].

**Fig. 10.** Submersible turbine (Underwater 100) [47].

areas [2,6] because they are used to generate electricity for lighting, TV, radio, desk fan, ice-making and refrigeration, powering farming tools, food processing, and battery-charging in rural areas [2,5,6].

*Tesla turbine*. This is a bladeless boundary layer, multiple-disk, friction, or shear force turbine [11,57] invented in the 19th century by Nikola Tesla. It has multiple rotating disks that employ the fluid viscosity to generate electricity. Many researchers have fabricated and tested the Tesla turbine to evaluate its

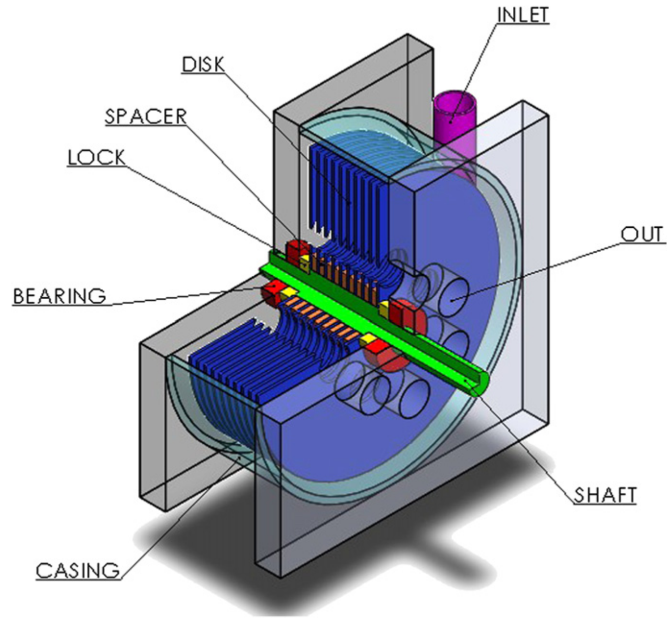


**Fig. 11.** Cut-out view of a Tesla turbine [11].

performance in order to improve its overall efficiencies [11]. Recent relevant studies have been carried out by [11] to design a Tesla turbine for pico-hydro applications. In the design, the flow and head required to generate 300 W with high efficiency (80%) were 2.5 L/s and 20 m, respectively. Despite the challenges that remain in the use of Tesla turbines for pico-hydro generation, including low power densities and efficiency, Ho-Yan views Tesla turbines as feasible for use in pico-hydro power generation because its design and components are simple, easy to manufacture locally, and has lower cost and maintenance requirements compared with blade turbines [11]. These features make the Tesla turbine an ideal standalone option for low-income households in rural areas [11]. Regardless of the feasibility and valuable features of the Tesla turbine for pico-hydro application, the two challenges, heavy weight (300 kg) and large size, of the turbine have made it neither competitive nor cost-effective because the size of a small hydropower plant is very critical in the cost-effectiveness of the investment [11,58].

### 2.3. Key R&D tasks

R&D is important in turbine performance improvements and affordability [59] of the pico-turbine. Many organizations have been engaged in the R&D of pico-hydro turbines since their introduction and spread of usage in developing countries.

Researchers and proponents of pico-technology have forwarded suggestions for future R&D and initiatives to add significant value to the current pico-technology for rural electrification in remote areas [25,27,60]. With the advancement and maturity in pico-hydro technology [60], other opportunities for further R&D have emerged, including, power quality improvement, integration with other renewables or as a part of a hybrid energy system, innovativeness, head loss, technology exchange, and universal design.

#### 2.3.1. Power quality improvement

Any improvements in electric equipment such as generators [4] and ELCs [61] are enablers of significant improvement in the power quality of pico-turbines. According to [61], power quality can be improved for both balanced and unbalanced loads

by increasing the number of pulse diode rectifiers. For example, the conventional ELC has high Total Harmonic Distortion (THD) for the generated voltage and current due to the nonlinear behavior of ELC caused by the presence of a six-pulse diode rectifier [61]. However, with the proposed 24-pulse diode rectifier ELC, a significant improvement to the THD of the generated voltage and current was found due to the minor distortion in generated voltage and current through the maintenance of constant power [61]. Consequently, improving the regulation of the isolated asynchronous generator led to the improvement of power quality [61].

#### 2.3.2. Integration with other renewables or as a part of a hybrid energy system

The integration of pico-hydro system with other renewable energies such as solar, wind, biofuel, fuel cell, and distributed energy technologies [16,60] can extend the life span of the unit and reduce the scheme's operating and maintenance costs.

#### 2.3.3. Innovativeness

Researchers have persisted in their endeavors to optimize the turbine performance or to test a new concept for low head site. Recently, [62] designed a new type of kinetic hydropower generator suitable for use in small shallow rivers and channels. The prototype extracts energy from the conversion of energy sourced from a flow of water using a series of sails rotating around an elongated vertical axis turbine. Although the performance was very low, the new system showed great promise with regard to electrical power generation [62].

#### 2.3.4. Head loss

The paucity of research on head loss has made it imperative that intensive studies be conducted for pipe loss analysis through the latest software technology and the utilization of advanced material (plastics and new anti-corrosion materials), which can reduce total pipe losses [63].

#### 2.3.5. Technology exchange

There is a need to adapt and apply other proven technologies that have been utilized in similar applications to pico-turbine. Researchers have continuously explored techniques that can lead to significant contributions to the development of pico-turbine. For example, [4] designed and tested an Axial Flux Permanent Magnet generator for pico-hydro turbine. This well-proven technique has been verified and confirmed, and its use can be seen in varied applications such as electric vehicles and wind turbines [4]. Such technology could help enhance the availability and affordability of the turbine, which could revolutionize the economics of rural electrification.

#### 2.3.6. Universal design

The main aim of researchers in pico-hydro R&D is the universality in the design, which can be achieved through the standardization of pico-turbines, thereby enabling it to be manufactured locally in developing countries [14,64,65]. This technique results in the cost-effectiveness, simplification, and spread of pico-hydro technology in remote areas [14,64,65] for electrification. Currently, communities in remote areas such as in Nepal and Vietnam can manufacture pico-turbines in basic fabrication facilities [64,65].

### 2.4. Modification for performance improvement

Fortunately, some software tools available in the market, such as CFD, enable researchers to analyze and simulate changes to the turbine rapidly for performance improvements.

The key roles of modification in the pico-hydro field are to make feasible changes simplifying the turbine design or to generate revenue. Examples of pico-turbine modifications are as follows:

- [64] used CFD to simulate and analyze the design of a modified rotor of pico-hydro propeller turbine, and found that the overall mechanical efficiency measured at 65% after modifications were made. They concluded that a more accurate selection of right runner design and turbine operating speed is needed for the available flow rate at the site in order to improve the performance.
- [14] proved that over 70% turbine efficiency can be achieved for modified existing propeller pico-turbine when guide vanes are removed and a simple chamfer on a critical corner is fabricated. These modifications lead to a simplification of the pico-turbine manufacturing process and a reduction in material cost [14].
- After [23] and other research organizations modified the Pitch Circle Diameter turbine housing to avert windage loss and replaced the motorcycle dynamo with a car dynamo, efficiency was improved significantly and power output rose by 66.6%.

## 3. Pico installation

Pico-technology is a mature technology for rural electrification, and thus many end users can install it either on their own, with the help of local technicians, or by referring to their friends already using it [6]. However, for areas where pico-technology is not well established or for someone interested in pico-hydro for the first time, [5] presented a simple manual to provide basic information about pico-hydro technology and to act as a guide for the selection and installation of pico-hydro turbines.

## 4. Pico hazards and safety

In remote areas, safety is often far below basic standards and are often ignored, thereby posing danger to human health and safety [12]. Electric cables are the most critical precautionary elements in pico safety because they carry electricity and can pose a significant hazard to pico users. Thus, users are strongly advised to use high-quality cables that have advantages such as strength and durability, are safer, and have less current leakage [15,66]. Cables are also among the more costly elements in pico hydro schemes because their length can stretch to up to 1.5 km each [66]. Unfortunately, many low-income households choose cables without insulation [6,15,33,67] and with small diameters (1.5 mm). Worse, some even use second-hand cables of different sizes and quality [12,15,67]. The danger behind the use of non-insulated cables with small diameters are voltage loss, breakability, and difficulty to recognize when hanging very low in simple bamboo poles or lying on the ground, which most pico users encounter [12,15]. This practice puts pedestrians at risk of electric shock or even death when they accidentally touch non-insulated cables.

Statistics show that two to four people a year encounter serious accidents due to the misuse and individual installation of pico hydro turbines [68]. In ensuring that the pico-hydro scheme is safer for users and its performance is optimized, the safety tips below are critical and strongly recommended:

- *Install load controller*. Although an ELC is expensive, costing about US$200, it provides constant voltage to electrical appliances and equipment and protects them from damage [66]. Thus, the life span of the generating unit will be extended significantly, and monetary wastage from the frequent replacement of electrical appliances and equipment can be avoided [66].
- *Install Residual Current Device* (*RCD*). Pico users should have an RCD, to protect themselves against electric shock. In addition, the RCD will only cut off the user with faulty devices and equipment rather than all the users [38,69].
- *Use good-quality cable*. Echoing the above discussion, it is wise to be more cautious in selecting the correct cable and not to think of cost savings at the expense of quality in order to avoid indoor and outdoor electric shock [69].
- End users should be trained and involved in the installation of the pico hydropower project to raise awareness of electrical hazards because many of them lack knowledge on the dangers of electricity [70].

## 5. Scheme and components cost

Listed below may be all the components and activities that constitute the capital cost of a typical pico-hydro scheme, whether at the individual or community level:

> Survey, turbine, generator, controller and protection, distribution system cable, electric pole, house wiring, energy saving bulbs, penstock, draft tube, installation, transportation, importation and nationalization, house-wiring labor, civil works, training, operation, and maintenance and warranty if any.
> This paper will deal with the salient cost considerations for individuals planning to use a new scheme, including turbine cost, total scheme cost, and cost of electricity per kWh, in order to compare it with other alternatives.

### 5.1. Turbine cost

The costing for common types of pico-hydro turbines in use in rural areas has been traced and is listed as follows. A 100 W unit is sold at US$14–US$30 [6], a 200 W unit is sold at US$20–US$200 [2,6,71], a 450–500 W unit is sold at US$40–US$1000 [2,6,71], and a 1000 W unit is sold at US$260–US$1000 [2,71]. Note that the price range between the lowest and largest values for a certain unit is rather large due to the following factors:

- *Transportation costs*: Even within the same country, there will be a price difference in transportation costs because some areas are very remote and thus require the use of different types of transportation, for example via air and sea [1]. The costs of international transportation, which are estimated at US$210 per unit for 24 PowerPal complete systems T5 (up to 2 kW), should also be considered [12].
- *Import costs*: Customs duty is undoubtedly a major obstacle to the dissemination of renewable energy because it raises the original cost by up to 40% [2,72]. On the other hand, it can be seen as a key promoter of the locally manufactured approach.
- *Quality*: Low-quality units are usually made in China and are the cheapest in the market, reasonably priced quality products are from Asian countries such as Vietnam and Nepal [2], and high-quality and high-priced units are from Western countries such as Canada [44].
- *Power*: Based on the above costs, the higher the output unit a user chooses, the higher the price he has to pay.
- *Head*: Low head unit is cheaper than high head unit for the same watts [2]. The high head unit is, however, almost smaller because a low head unit is the highest unit in demand in the pico market given that low head sites are widely available in nature and are found particularly in areas with heavy annual precipitation in the form of irrigation channels, small rivers, and waterfalls. The large demand for low head unit also enables manufacturers to standardize it and produce it in bulk. Thus, customized units are avoided and the price of the low head unit decreases as the demand for more units increase. This correlation is a basic concept of economics and is explained elsewhere. The minimum price is likely to be for locally manufactured pico-hydro turbines at the local marketplace, whereas the maximum price can be considered for door-to-door delivery. For example, in Vietnam, the 200 W system costs US$45 and for export it costs US$80 [2].

### 5.2. Total scheme cost

Claiming that the total scheme cost will be the same for different sites at a fixed output is difficult because the pico-hydro scheme is a site-specific project and there are other variable costs incurred, such as import and transportation costs. Overdesign can also be a tricky issue when pico users realize their actual output power is lower than the designed turbine power [66]. Thus, they utilize less power than what they pay for. The average total scheme cost is found to be at US$3000/kWh [1–3,5,15,38,69,71–78]. A lower cost can be achieved through optimum design and smart selection of scheme equipment. Nevertheless, higher scheme costs could be the result of a lack of suitable turbine design [5,36], a lack of knowledge on pico-technology [5], or deficiencies in conducting a good cost-effective approach.

### 5.3. Electricity tariff

The costs of pico-hydro electricity tariff are traced and found to be in the range of US¢10/kWh–US¢20/kWh, which is in agreement with the findings of [25,79]. The range can be taken as a reference for new projects to measure the extent of deviation from this range and use it in the discovery of reasons leading to the increase in electricity tariff cost.

## 6. Pico users

Cost-effectiveness, continuity, sustainability, and recoverability are key motivations for using pico-hydro technology by the following users:

*Low-income households*. Pico-hydro is designed mainly for rural electrification to allow low-income households to enjoy the use of standard electrical appliances such as lighting, televisions, radios, refrigerators, fans, and food processors [2,5,15,76,80], and to provide mechanical power for driving agricultural equipment such as grain mills and pumps, or handicraft activities [3,5,15,25,80] that help rural communities increase their income.

In addition, the utilization of pico-hydro technology for recharging auto batteries [2,3,5,15,25] and portable equipment such as mobile phones has provided added convenience to rural areas [3,25].

*High-profit company*. Far from the traditional use of pico, Motorola, Inc., has found that the sustainability, low cost, and low maintenance of the pico scheme make pico-hydro technology an ideal solution for power generation when a grid connection is not feasible for wireless communication network-based stations [81].

*As an energy-recovery device*. Pico-hydro turbines are considered as a good energy-recovery device because pico turbines can run at very low head and flow [2,6,14], making them more suitable for energy recovery. For example, they can utilize energy from wastewater treatment plants [82,83]. Recently, [84] showed interest in using very small pico-hydro schemes that are expected to generate 10 W from utilizing the kinetic energy of the water that flows through domestic pipes and use it for battery recharging for future use, particularly during the power outages. More recently, [10] designed and tested a pico-hydro turbine for their university campus by utilizing 2850 W from dissipated energy at the lower end of the distributed pipe generally at the entrance to the water treatment plant.

## 7. Cost-effectiveness

Compared with other small-scale renewable (e.g., wind turbines and PV solar home systems) and conventional energy (e.g., small petrol and diesel generators) options for remote areas [2,14], the pico-hydro scheme has been proven to be the most cost-effective solution for rural electrification [4,9,12,14,25,36, 64,85–87]. However, in the event that a pico-hydro site is available [14,25], it must be checked first [85] for cost-effectiveness. The following factors [1,2,5,6,9] are included in the checklist: less payback period (less than six months), saves money (no fuel), continuous electricity (no battery needed), affordability, driving extra mechanical load for income generation, sharing through the community, easily and locally manufactured even in a basic workshop, and flexible design. Even for a high-quality pico-turbine [2] and in very isolated areas where load demand is extremely very low [22], pico-hydro turbines are still an affordable option and provide a convenient electrification source for low-income households in less developed countries [2]. Moreover, [71] created a guide based on information gathered from available public sources. The guide contains technical specifications such as light intensity and life span, and some price estimations such as capital cost and operation and maintenance cost of the 50 alternatives available in the market as an option for rural electrification in order to end the use of kerosene for lighting. It is not surprising that the pico-turbine was given an A grade among the other 50 options in terms of high lighting service delivered and payback period (less than six months). This guide shows that kerosene lamp users pay approximately US$4 as monthly fuel costs per lamp with poor lighting for 4 h a day. In comparison, pico users pay US$0.5 for 1 W of LED or US$0.04–US$0.1 for 1 W of compact fluorescent lamps (CFLs) [13] per month (up to 16 h a day) and enjoy more brightness, good-quality indoor environment, and less energy expenditure.

Pico users enjoy more lighting services than kerosene users and spend less money on power because the latter pays three times more than the former. Recently, [72] found that pico-hydro hybrid systems (pico-hydro/biogas generator/battery systems) are more cost-effective than a single-wire grid extension when remote villages are further than 12 km from the nearest grid. Small-scale hydropower is also confirmed to be an environmentally friendly energy resource [88], and will remain as the largest resource of renewable energy in the world [89] at least for the next decade [79]. On the other hand, low head and low flow sites will be the dominant hydropower market for the present time and in the near future [88].

## 8. Factors that help the pico-hydro scheme succeed

Many crucial factors have promoted pico-hydro schemes and made it successful for rural electrification in less developed countries. This paper highlights these factors, which are discussed further below.

### 8.1. Community involvement

This factor is given more priority by many experts because it breeds two advantages:

- *Lowers civil works cost*. Pico scheme is distinguished among other hydro sizes by the low civil works cost, which accounts for no more than 5% of the scheme costs [25]. The community can offer voluntary labor when digging channels and penstock trenches, joining penstock pipes together, installing the electricity distribution system and house-wiring, and providing local available materials (e.g., wood, boulders, clay, soil bags), which can result in significant savings in concrete use [25]. [90] found a direct correlation between head and concrete volume in relation to the situation where the head goes low and more concrete is needed for the direction of the flow. All of the above civil works are given free of charge because of the community's involvement, if not, it would constitute a heavy burden on total cost.
- *Ownership*. The sense of ownership that the community will have of the pico-hydro scheme will sustain the practice of better management, which leads to more concern on the maintenance and operations of the scheme, boosts the relationships between community members, and encourages the community to invest in a good-quality scheme in the future [25].

### 8.2. Locally manufactured

Locally manufactured products are not necessarily always cheaper than imported products. For example, pico-turbines imported from China are cheaper than pico-turbines manufactured in Vietnam [6], because China is the home of hydroelectric power and has thus far been the leading manufacturer and market of small hydropower units [12,36]. As the leader in small hydropower units, China has the capacity for mass production, which allows the units to be priced lower,and thus dominate the small hydropower market anywhere.

Second, pico-turbines brought into countries are not subjected to customs tax because most are smuggled through the border between the two countries as reported by [6], accounting for why the Chinese 100 W units dominate the Vietnamese market with over 90% coverage. This is not the case for Ecuador, where there is no escape from the payment of taxes and duties imposed on imports [33]. These taxes and customs duties accounted for more than 35% of the price as estimated in the 31 pilot pico-hydro projects that have been established in two provinces of Ecuador [33].

If this tariff is taken into account, it could encourage the emergence of locally manufactured turbines. In the case of Vietnamese manufacturers, imported Chinese pico-turbines have gained a bad reputation due to [6] their short lifespan (two to three years), lack of reliability, lack of guarantee on any part of the system, manuals in Chinese, and no after-sales service and refurbishment (repair and maintenance cost) of the unit after one year, which is estimated to be the same as purchasing a new one [6]. The disadvantages in Chinese design have motivated the Renewable Energy Research Centre to endeavor in overcoming most of the weaknesses of the Chinese units and the result is a unit with a longer lifespan (typically five years) and higher output (200 W) for US$55 [6].

The Chinese turbines (100 W) appear to be cheaper, costing only US$20–US$30. On the other hand, when compared with the

Vietnamese turbines (200 W), which are sold for UU$55, the cost of 200 W Vietnamese turbine is equivalent to two units of 100 W from Chinese turbines (slacker tax), which is in the range of US$40–US$60. This finding indicates that the 200 W (one unit) Vietnamese turbine is within the price range of the Chinese 100 W turbine in terms of watts. The results of the comparison show that the locally manufactured turbine is capable of competing with turbines from other countries, with the added fact that taxes and customs duties are not accounted for in the Vietnamese case. Furthermore, the disadvantages of foreign turbines have proved to be advantages for local turbines. For example, the manuals will be in the local language and after-sales service is possible [6]. Recently, [12] evaluated the pico- and micro-hydropower market in Rwanda, and indicated support for the local manufacturing of improved turbines with a capacity at least up to 25 kW because the costs of pico-hydro in Rwanda is around 20% less than in Indonesia.

Based on the past experience of [12] in Indonesia, locally manufactured turbines are more likely to generate local hydropower experts that can contribute to the further development of pico-hydro in developing countries.

### 8.3. Management

Community members involved in management tasks should be aware of pico-hydro technology and learn how to manage and improve their plants from the experience of others. [91] investigated the factors that affected the success or failure of rural electrification schemes in 14 villages in Peru, and discovered that practicing better management approach is a key factor to successful revenue generation, effective performance, and lifetime of any off-grid rural electrification scheme in addition to technical support (installation, training), which is a necessity.

As these schemes are in isolated areas and with low profit margin that make them less attractive to most investors, [92] suggested that villagers should own and manage their schemes to ensure that they are operated at peak performance.

### 8.4. Operator

Operator plays a significant role in pico-hydro projects and should not be underestimated because he/she is responsible for the performance of the overall scheme by ensuring that it runs efficiently all the time by carrying out preventive maintenance, technical error-finding, and repair of broken parts [38,93]. For example, [12] found that the lack of technical expertise in Rwanda was a major obstacle in faster and more efficient development of the available market potential. Furthermore, [85] noted lack of maintenance as the major cause of a large number of off-grid electrification project failures, which will certainly increase future operating expenses. Hence, there must at least be a local technician to avoid extensive training, or a new operator who possesses a basic understanding of electricity and is involved from the beginning of the installation scheme to ensure that sufficient training is given and received by the operator [38,93]. For best results, operators should be provided an equipment manual including complete circuit diagrams and maintenance schedule [38,93]. Operators should be paid for their services on time to guarantee that they will pay proper attention and keep the scheme running smoothly [38,93].

### 8.5. Smart management for loads distribution

Smart load management will result in fair electricity usage among community members according to their subscribed package. This method will also generate income by connecting farming equipment such as mills and sawmills to the generator or selling power to another customer (e.g., grid). This practice includes load limiter, electricity storage, energy efficient lamps, and electricity investment.

- *Load limiter*. Load limiter is the cornerstone of the successful management of load distribution. This device is used to guarantee the smooth and fair load distribution among shareholders and automatically terminates the connection if consumers withdraw more current than they are subscribed to [69,93]. Such features will prevent conflict between end users and protect the generator from overloading and voltage fluctuation [69,93].
- *Electricity storage*. When the pico-hydro scheme generates more power than needed and there is no interest for income generation, this extra power can be stored and reused when needed because electric energy can be converted into other energy forms. For example, heat and heat energy can be stored in water, and then used for cooking or supplying hot water for showers in cool weather [29].
- *Energy-efficient lamps*. Using efficient lamps in pico schemes provides people with lighting benefits because these lamps only use a few watts to emit bright light. These lamps also have longer operating life and are an incredibly energy-efficient appliance [1]. For example, the use of LED has been recommended by [1,94] in pico-hydro schemes because of the mentioned advantageous characteristics. CFLs have also been found to be cost-efficient even when using high-quality lamps [77].
- *Electricity investment*. Rural populations need electricity mainly for lighting at night [77]. Therefore, there will be an opportunity in the daytime to use this energy to drive some agricultural equipment to generate income, or sell the residual power to the grid to help in the payment of debt installments [3,5,37].

### 8.6. Survey and cost reduction

According to [5], a survey is extremely important in the consideration of a new site for pico-hydro scheme. A survey is the initial step taken to confirm the economic and technical feasibility of a pico-hydro scheme. However, pico contractors need to conduct two kinds of survey, namely, technical and demand survey.

- *Technical surveying*. This survey requires equipments that vary in terms of cost, complexity, and accuracy. Cheaper methods similar to those in [38] should be used to reduce time-consuming and technical-surveying cost. These equipment are used to measure the flow rate and available head. The expected annual hydro power of the site can then be calculated to determine the suitable turbine size and to identify the best powerhouse location [5,77]. Moreover, low-cost handheld GPS systems can be used to ascertain the distribution of houses inside a 1 km radius from the best powerhouse location and stream on the map [38].

Results obtained from the technical survey are very useful in deciding the best powerhouse location, which depends on several variable factors such as penstock, cable, water right, accessibility of the site, and civil works. Some of these factors are discussed below.

- *Demand survey*. Should be conducted to ascertain the following information [5]: main usage of load (lighting or mechanical), tariff affordability (how many customers), ownership (community

or entrepreneur or single use), and grid strategy (accessible or in near future).

Traditionally, the design and execution of site surveys for pico-hydro project planning take a long time because of its site specificity. The time taken in the process may add extra cost to the capital. According to [3], these two processes can be reduced by turbine standardization and the use of GPS, which only require one site visit to identify the best powerhouse location for utilizing the maximum head available and using some available computer software for the best selection of pipe dimensions such as diameter, length, and cable layouts. Technical survey of the site helps pico contractors examine all the different scheme layouts available and determine the cheapest scheme layout. [5] gave an example of four possible scheme layouts. Referring to the example, penstock and cable length can be considered as variable factors in selecting the best powerhouse location because there is more than one option to consider. Thus, the layout that gives the shorter penstock and cable will be the cheaper scheme layout.

Finally, it is wise to underestimate the head and flow rate in order to remain realistic and avoid the chances of poor compatibility between the turbine and the site characteristics.

### 8.7. The right choice of scheme equipment

New users must think twice and ask an expert before buying pico scheme components. Failure to select proper components will result in poor scheme performance. As a result, users will pay more than they need in terms of kW/h. Each component of the scheme has its own significance. The following are the core components of a pico-hydro scheme.

*Turbine*. Turbine must be carefully selected because it is the most important equipment of the scheme. The turbine utilizes the hydro power and converts it into mechanical power [24]. There are different turbine designs that have been recently developed [24] by various manufacturers in Europe, South Asia, and North and South America. Turbine selection in terms of quality and cost is more difficult because there are several varieties to choose from. End users have a hard time deciding which type of turbine should be used that will satisfy their needs [95]. The traditional turbine selection criteria depend on the site characteristics, mainly head and flow availability [95]. Low-income households in rural areas have developed their own selection criteria to cover several technical issues such as cost-effectiveness, community budget, repeatability, easy installation and maintenance, local availability, and reliability [53]. Obviously, the best selection is the most efficient turbine. However, this method does not always work, especially if other options can provide a cost-effective solution for electrification. For instance, there is a growing interest in rural areas in using PAT because pumps are simple equipment with no special design, readily obtainable in most less developed countries, and their installation, operation, and maintenance can be done by local rural residents [53,54]. It is also a 2-in-1 option where turbine and generator always come in a set [55].

All these benefits make PAT an attractive and significant option for low-income households. [25,53,56] proved that using PAT can provide a long-term system that can be reproduced for rural communities where the purchase of hydro turbine is considered too expensive [50,53].

The basic electricity demands in remote areas are for lighting and radio [77], which means that turbine selection is based on end users' affordability, that is, in other words, for the same watts, end users will prefer to buy cheaper units instead of highly efficient units. That is why cost, not efficiency, is the most important factor in the consideration of a consumer's purchasing power of small hydro turbines [96]. This phenomenon was likewise observed in the Vietnamese market when it was inundated with 100 W Chinese turbines for a very low unit price, even though the Vietnamese designs are more efficient and reliable [6] and within the price range of Chinese unit in terms of wattage. Right turbine selection is not always as easy as it seems. Indeed, a poor-quality turbine is linked to excessive and frequent maintenance and repair works [12]. Moreover, a mismatch between turbine and site characteristics is not only seen as wasting pico users' money in an unaccountable manner. [64] found that a mismatch between the turbine rotor and the available flow rate is significantly affected by the turbine performance. However, [66] mentioned that several users who have not come across pico-technology have installed their units on their own or have requested help from others who have used a pico-hydro unit before. This practice happens because of the lack of an instruction manual, and because pico suppliers do not provide after-sales service experts (certified technician or consultant) who can match the turbine output and the load required and accurately install a pico-turbine to run efficiently [66]. As a result, users pay more for their incorrect estimation when they install a high-output turbine by utilizing less power [12,66]. Turbines working under these situations also produce high fluctuations in voltage, current, and frequency, which reduce the life span of the turbine and damage the appliances [66].

*Generator*. Several experts have found that the induction generator is the right choice for pico-hydro schemes in rural areas. It is highly recommended for its cost, availability, and reliability [14,28].

*Cables*. Cables bring electricity from the pico-hydro units to the homes of end users. The length of the cables could be as long as 1.5 km [15,66]. For this reason, cables are the most expensive component of a pico scheme, costing even more than the pico-turbine [15,66]. For example, in Xiengkhuang Province, LAO PDR, the cost of imported cable from China is around LAK 130,000/70 m [66] which is equivalent to US$0.2/m [97]. However, selecting good-quality cables that are safer, not easily breakable, and have less current leakage (more lighting can be obtained) can extend turbine lifespan, protect electric appliances [15,66], and prevent users from electrocution [69].

*Penstock*. Penstock is a pipe that brings water from the highest to the lowest possible point in a turbine for power generation [14]. Further discussions by [35,95] explain the different possible hydro scheme layouts on a low, medium, and high head, and the appropriate use of a canal or penstock for each particular layout.

The selection of penstock diameter is very important because it is the most critical factor that contributes to head loss, as can be seen in Eq. (2) where the minimum head loss that can be achieved using typical costs is between 5% and 15% of the gross head [14].

$$H_f = \frac{flQ^2}{3d^5} \tag{2}$$

where $f$ is the friction factor, $l$ is the pipe length, and $Q$ is the volume flow rate which can be considered as a constant when the turbine is fixed in its final place, $d$ is the pipe diameter, and [14] is the final parameter that can be taken into account to minimize head loss. [98] determined the diameter of penstock that gives the optimum power output, which occurs when head loss is 33% of the gross head. [14] recommended going for a larger pipe diameter than a smaller one that gives 33% head loss in order to improve the overall efficiency of the scheme at minimal extra cost. Both high density polyethylene (HDPE) and PVC pipes are available in most less developed countries. Selection is therefore mainly dependent on which pipe is the cheapest. For example, in Nepal, HDPE pipes are the preferred choice for penstocks because they are cheaper than PVC pipes, having a starting price of 3.78 (US$/m) [77]. In addition, it is more flexible, smooth-walled, strong, and does not degrade in sunlight [77]. For any total capital

cost analysis of pico schemes, penstock cost should agree with [25], who used PVC pipe with 90 and 160 m length for different projects in Kenya and found that the cost of penstock comprise around 8% of the total project cost. Therefore, different possible hydro scheme layouts should be examined to get the shorter penstock length and minimum pipe losses, which certainly improve the overall scheme efficiency and result in low electricity cost (US$/KWh).

### 8.8. Software for optimizing overall turbine performance

Computational fluid dynamics (CFD) has been proven to be a helpful tool widely used by engineers for the simulation, design, and analysis of complex three-dimensional flows in turbo machinery, and for diagnosing problems such as energy loss and its solution [14,64]. For example, [64] used CFD to design a new rotor and to develop a standard design procedure for pico propeller turbines that can be easily manufactured in less developed countries. Turbine performance can also be predicted before the manufacturing stage, which allows the designer to make any necessary modification to optimize overall turbine performance.

### 8.9. Standardization

Several experts desire the standardization of pico turbines for the following considerations:

- Lowering cost while maintaining good turbine quality and safety [64,85].
- Local manufacture is possible in less developed countries [64].
- Enabling duplication of similar schemes at other locations around the globe [14,73].
- Increasing of rural electrification rate due to the above considerations [85].

On the other hand, [14] cautioned against placing extreme focus on lowering the price of pico-hydro scheme because this will negatively affect quality, performance, and safety, giving pico-technology a bad reputation in the electrical market. At the end of this discussion, [99] mentioned a very important example about how the success of pico-hydro technology in a remote village of Kerala State in India inspired the installation of 30 pico-hydropower generation units for 30 low-income households in the village. Standardized modules have become available since then. Therefore, the production of good-quality turbines in developing countries is in the hands of rural communities through local workshops [12].

## 9. Pico market and demand

The future will be prosperous for the pico-hydro market because pico-hydro has been proven to be the most cost-effective renewable energy option for providing electricity to rural areas [3,4,14,100]. Hence, pico will remain in the rural electrification menu as the best option for supplying electricity to low-income households and is unlikely to lose its share easily in the rural energy market, even if other renewable technologies such as PV and wind become affordable or fossil fuel becomes cheaper. This possibility is not expected to happen now or in the near future because fossil fuel remains the main provider that meets the high demand for energy consumption worldwide [101]. Quite the contrary, the potential for the robust expansion of pico is massive [4].

Pico is the undisputed winner wherever viable sites are available and continue to gain other off-grid options market share such as solar [5,25,102–105], battery [25], wind [5,101], kerosene lamp [71], and petrol and diesel generator [5,106,107].

The increasing demand for pico-turbine is prevalent in the global pico market because it have been proven to be the most promising solution to rural electrification. Below are some factors that are likely to increase the demand for pico-turbine in the rural energy market:

*Rural electricity demand*. Rural demand for electricity can play a significant role in influencing pico demand in less developed countries because the demand for electricity in rural areas in less developed countries is mainly driven by the national rural electrification program and population growth.

- National rural electrification program. In many less developed countries, policy makers provided a series of policies and measures to promote and facilitate access to electricity using available renewable energy resources in order to end the use of biomass, coal, and kerosene [29,108,109].
- Population growth. Despite the rapid electrification rate in light of the current progress, the number of people who do not have access to electricity accounts for 1.6 billion in rural areas [13]. According to [110,111], the number of people who lack access to electricity will increase to more than 400 million in 2020, which means that a large amount of demand is yet to be met [101]. [25] mentioned that although the rural electrification rate in 2003 was about 10,000 households per year in Kenya, it hardly meets the rural population growth. In addition, although some less developed countries such as Brazil, Bangladesh, India, Morocco, and South Africa have achieved higher grid connection, only 20–30% of the rural population have access to electrical networks because of the rapid rural population explosion [112].

*Technology*. While pico-turbine is a mature technology, it has not seen in-depth development from the technological aspect [14]. Rapid advancement in other technologies, especially in the field of computer software such as computational fluid dynamics, have helped designers improve the efficiency and performance of pico turbine [14,64], and make it more efficient and cost-effective over other off-grid options as well as more affordable for consumers [6].

*Media and communication*. As the technology acquires maturity and becomes more advanced, several types of modern equipment are becoming more affordable to low-income people, such as TVs, mobile phones, and energy-efficient lamps. [25] mentioned the indirect impact of media and communication technology on electricity demand when the advent of the television in the 90s became cheaper, enabling low-income people to buy it. The demand for TV led to an increase in the demand for any available electricity sources such as batteries in rural areas. This is similar to what happened recently in some rural areas when mobile phones and their call rates decreased [25]. Low-income households in less developed countries turned to the exploitation of feasible renewable energy such as solar, wind, and pico-hydro for generating electricity and recharging their mobile phone batteries [25]. It was not only individuals in remote areas that had a huge impact on pico demand, but also cell phone companies who had become valuable clients contributing to the increase in pico demand. For example, Motorola Inc., found pico the best solution for power generation in wireless communication network base stations to expand their business into remote areas [25,81].

*Difficulty to access electricity via grid*. Grid extension is the most depressing factor to pico demand because it offers lower tariff than other options (genset and renewable energy resources) and can secure continuity of the electricity supply [12,34,66]. [66] conducted a survey and found that several dealers complained

about drops in pico sales as a result of grid connection in several pico customers. Unfortunately, grid extensions for remote communities are still unaffordable and unprofitable to most grid investors due to the low power loads of rural communities [1,5,63]. Consequentially, pico-hydro is still in demand even in areas where grid lines can be seen passing over or are very close to the houses in rural areas [108].

For example, in Kenya, even though the grid is near the community of Thima, people were unable to connect to the grid due to the high grid investment cost. The community could neither afford it nor have access to funds [113]. Another example can be seen in the rural households in Vietnam who have lost their hope for grid connection and have chosen off-grid connection to meet their electricity needs instead of waiting years to get connected [6].

Although there are a large number of power stations around the globe with the most electricity generated for national grid [114], millions of people will still lack grid connection for many years to come (15–20 years) [6,12,115].

*Time frame for grid extension*. [85] suggested the use of renewable energy sources instead of waiting for grid extension if the time frame for the grid extension process is more than five years even if the grid extension is found to be feasible or cost-effective.

*Grid tariff affordability*. Thermal power stations are the main electricity generator for national grid in many countries. Thus, tariffs are mainly influenced by fossil fuel price fluctuations. However, as most governments have currently decided to end subsidies on fuel prices, grid tariff is no longer subsidized and are subjected to the rise or fall of pricing according to the fossil fuel market price [6,75,86,109,116,117]. Thus, fuel price will play an important role in grid tariff calculation. As grid tariff increases, more grid consumers will start considering bringing their energy bill back to before by selecting energy-efficient appliances that have earned energy star labels or appliances that use 20–30% less energy than conventional models [118]. In contrast, when grid tariff becomes unaffordable and more households are unable to pay for it [115,119], consumers will consider alternative sources to grid connection such as biomass, kerosene, solar, wind, pico-hydro, and others for their electricity supply or for lighting [6]. For example, the Vietnamese government ended the grid electricity price subsidy since 1995, which forced several low-income households to think of other options for electricity generation because the new tariff was no longer affordable to most of them. As a result, the Vietnamese hydro market has shown a larger increase in the demand for pico-turbine [6]. Moreover, [108] reported that a majority of low-income households in urban and semi-urban South Africa have access to electricity, but they could not afford the grid tariff. Therefore, many low-income households continued to use non-electric fuels for their energy needs.

*Grid quality*. Power stations in several less developed countries take time to develop to meet future energy demands [115], which results in poor performance of grid connection and leads to voltage fluctuations and frequent power outage [120,121]. For instance, in Nepal, power outage occurs from 8 to 12 h per day, and in Indonesia outside Java, 3 to 5 h of power outage per day is normal [12]. These problems caused damage to domestic appliances and manufacturing equipment, slowing down production activities and other negative effects [115]. For these reasons, many grid consumers use pico-hydro as a backup to avoid such inconveniences [33].

*Geography of the site and distance from grid*. Mountainous and remote areas are still the birthplace of millions of people around the world. Unfortunately, these sites will remain economically unfeasible for grid connection because of site inaccessibility, low population density, and distance from the national grid. These areas are associated with high generation and transmission costs and low demand load [1,63,85,122], where the demand for electricity is mainly used for lighting and powering radios and small television sets [25,115,123]. These small loads can be met by other options such as PV, battery, wind, SHP, [124–126]. Not surprisingly, those sites are often recognized with the abundance of hydro power [63,95,122,127] due to huge annual rainfall [68] where many irrigation canals, streams, and small waterfall are formed [6]. These sources could generate a massive demand for pico-hydro because of renewable energy especially SHP, which is proven to be more attractive than grid extension for providing access to electricity in such small remote villages [63,95,122]. For example, in Vietnam, several households have adapted off-grid technology for electricity supply as a result of the favorable hydro resources and the presence of cheap pico-hydro turbines [33]. [122] claimed, in some cases, that if the number of households in the rural community is less than 50, it is more feasible to use hydro power instead of grid extension, although the distance of the grid extension is only 2 km. [115] simulated and found that the breakeven grid extension distances of micro-hydro hybrid system in the remote villages of Cameroon is 15.4 km. Similar to the above discussion, [122] found that it would not be economically viable to provide electricity access to more than 24,500 villages in India.

*Government*. People will probably shift to green energy because their governments have an honest desire to reduce greenhouse gas emission, which can be achieved by increasing the price of electricity produced by thermal power, reducing taxes [95], importing duties on equipment and parts used for renewable energy electricity generation, encouraging private sectors to invest in electricity generation based on renewable energy sources [8,95,99], and sponsoring renewable energy schemes [95,128] through particular funding mechanisms that offer grants toward small-scale renewable energy projects. An example of this funding is Clear Skies in the UK, which offers a grant up to 50% of the project cost [95], or the Performance-Based Incentive in the USA [85]. For example, as Greece has started subsidizing electricity generation projects based on renewable energy sources up to 50% of the project costs [129], several private investors have formally shown their interest in investing in small hydro power schemes across the country [130]. However, when it comes to renewable energy awareness, the role of the government in developed countries is more effective and actionable than in less developed countries. Each government, however, can significantly contribute to the demand generation of pico-hydro in the electrification market. For example, the US government recently adopted a program known as Federal Tax Credits, which promises to provide households who buy energy-efficient appliances or those who generate electricity from renewable sources, an energy scheme 30% off the cost or up to US$500 per 0.5 kW of power capacity (including installation) [131]. As a result, several small hydro sites around the world will become technically and economically viable especially for rural electrification when governments take these outlines as their commitments:

- Remove legal and administrative barriers or any other barrier that make it difficult for low-income households to access electricity through the use of small hydro scale or prevent investors from investing in small hydropower [106].
- Undertake efforts to reduce global warming.
- Provide grant support to low-income households or fund small-scale renewable technology schemes.

*Environmental legislation regulatory* (*CDM*). The CDM, which is stated in Article 12 of the Kyoto Protocol, allows industrialized countries with emission-reduction commitments to implement an emission-reduction project in less developed countries [132]. Since 2006, more than 1650 projects have already applied for

funding from the CDM. These projects can reduce more than 2.9 billion tons of $CO_2$ emitted in the air [132]. Considering the global price of the CDM project, which is about 13 US$/tCO2e [133], selling carbon credit [85] can generate a carbon market liquidity above US$30 billion [134]. Recently, more than 3000 schemes have conformed to CDM, and by 2012, they will be able to reduce carbon emission by 2.5 bnt $CO_2$ [109].

A large number of people in rural communities lack access to electricity despite the viability of pico-hydro schemes due to their low-income conditions or lack of government funding. The CDM offers an opportunity for them to apply for funding to cut down the price of the more efficient and reliable pico-turbines by 11–12%, or about US$20–US$22 on the average size of unit expected to be installed (668 W). The CDM enables low-income rural households access to electricity, which will improve their socio-economic status, including health, education, and income [6,17,106,133,135,136].

*Switching to renewable energy resources*. There is an urgent need to find alternative resources to fossil fuel for the current energy situation and for future generations because oil, coal, and gas reserves will only remain for a period of 35, 107, and 37 years, respectively [137]. According to [101], there will be a huge world demand for energy, which is expected to increase by 44% from 2006 to 2030. Present demand and that for the next century will be mainly fulfilled by fossil fuel [101,137]. Undoubtedly, more $CO_2$ will be pumped to the air [114]. As a result, the price of fossil fuel is expected to rise steadily as the world faces a huge and continuous energy demand, and the oil and gas reserves begin to decline noticeably [18,101].

Hence, using fossil fuel to generate electricity can contribute to the increase in greenhouse gas emissions. This phenomenon will therefore lead to the use of available renewable energy sources to meet our daily electricity demand, reduce reliance on fossil fuel, and minimize the negative impact on nature in the future. Pico-hydro is an ideal solution for such problems. This technology can provide rural areas with sustainable and green energy [88]. Pico-hydro has always been considered the most significant renewable energy technology in many less developed countries. Pico-hydro is the most cost-effective (cheap and sustainable) option of electrification for low-income households living in remote areas beside waterfalls, streams, and irrigation canals [2,6,15,70]. Currently, however, there is an increasing demand for pico-turbine in some developed countries such as Japan because of increased awareness to reduce global greenhouse gas emissions on a personal level and their attempt to meet their energy demand [138].

*Its effectiveness as an energy-recovery device*. Low-income households are the main users of pico-hydro in less developed regions where it is mainly used to extract a few watts of electricity derived from natural waterfalls or irrigation channels. At present, however, high electricity tariffs and the move toward clean energy in order to contribute toward the reduction of $CO_2$ have made pico an ideal device for acquiring energy from wastewater treatment plant, chemical industry, seawater reverse osmosis, water supply system, and as a reduction valve [82,83,139].

## 10. Global market size for pico-hydro

The size of the global pico market has grown and expanded rapidly since its development in the South China continents and the surrounding countries in the late 1980s [2,15,17–21]. According to [17], there is a large potential in the global market for pico-hydro in less developed countries (Latin America, sub-Saharan Africa, Indian subcontinent, and SE Asia), which is estimated to be around 4 million units, as illustrated in Table 1 [136].

However, the actual market size is certainly larger than this number if disused or undeveloped water mill sites and other pico applications such as energy-recovering devices are taken into account. For example, there are 200,000 traditional water mills in India, Nepal, and Bhutan that could be upgraded at a low cost (US$800/kW) for low head pico-hydro schemes [94]. Some developed countries are facing a similar scenario. For instance, the UK has some 20,000 disused water mill sites that could be developed into low head hydro sites [63]. On the other side of the globe, the Latin American market is expected to experience rapid growth during these years and in the years ahead, because some countries have given a positive and convincing example of successful pico schemes that encourage others to use pico-hydro for rural electrification [33]. An estimated 1.23 million households could start using pico-hydro in Ecuador and the four other nations in the Andean Region (Peru, Bolivia, Columbia, and Venezuela) [33]. This estimation is based on rural electrification

**Table 1**
Global market size of pico hydro across Latin America, sub-Saharan Africa, South Asia, and South East Asia [136].

| Latin America | | Africa | | South and SE Asia | |
|---|---|---|---|---|---|
| Argentina | 12,400 | Benin | 4500 | China | 93,000 |
| Bolivia | 47,400 | Cameroon | 27,600 | India | 978,400 |
| Brazil | 524,300 | CAR | 7200 | Indonesia | 558,300 |
| Chile | 5200 | Cote d'Ivoire | 18,700 | Lao PDR | 10,000 |
| Colombia | 58,400 | Ethiopia | 97,800 | Malaysia | 30,600 |
| Ecuador | 35,700 | Gabon | 1700 | Myanmar | 48,600 |
| Guatemala | 8000 | Guinea | 9200 | Nepal | 292,500 |
| Nicaragua | 29,600 | Ghana | 33,700 | Philippines | 118,700 |
| Peru | 20,300 | Kenya | 80,200 | Sri Lanka | 170,600 |
| | | Lesotho | 2000 | Thailand | 272,300 |
| | | Madagascar | 46,100 | Vietnam | 153,900 |
| | | Malawi | 1800 | | |
| | | Mozambique | 9200 | | |
| | | Nigeria | 32,600 | | |
| | | Rwanda | 4900 | | |
| | | Senegal | 5500 | | |
| | | Sierra Leone | 32,100 | | |
| | | Tanzania | 37,900 | | |
| | | Uganda | 17,500 | | |
| | | Zambia | 3500 | | |
| | | Zimbabwe | 6000 | | |
| LA total (18.8%) | 741,300 | Africa total (12.2%) | 479,700 | Asia total (69%) | 2,726,900 |
| Analyzed 64.1% of total pop. | | Analyzed 65.2% of total pop. | | Analyzed 90.1% of total pop. | |

rates, different morphological areas in each country defined according to rainfall, topography, and how rivers are spread across the region, and factors of local capacity and willingness to pay [33]. Growth in this region will primarily be driven by affordability, reliability, maintenance support, and good quality equipment [33].

Although many countries in Latin America, sub-Saharan Africa, Indian subcontinent, and South and SE Asia have started exploring and exploiting their low head sites for rural electricity generation, South East Asia remains the dominant market for pico-hydro technology [4,9,140].

The countries involved in pico-hydro manufacturing or usage are Australia, Brazil, Bolivia, Canada, Chile, China, Columbia, Cuba, Ecuador, Ethiopia, Germany, Guyana, India, Indonesia, Japan, Kenya, Lao PDR, Nepal, New Zealand, Nicaragua, Malaysia, Mexico, Myanmar, Panama, Paraguay, Peru, Philippines, Pacific Islands, Slovenia, Sri Lanka, Swaziland, Thailand, Venezuela, Vietnam, USA, and Europe [2,6,12,136,138,141,142].

## 11. Advantages and disadvantages

Several low-income households prefer pico-hydro over other renewable energy resources such as wind and solar power because of its great advantages. Besides those advantages, the most important features of pico-hydropower are simplicity, affordability, and power continuity.

*Simplicity*. Pico-hydro turbines use simple technology. As a result, a variety of turbines can be manufactured locally [25,37], which gives pico schemes the advantage of reducing capital cost [1]. For example, a standardized design of Pelton turbine can be locally fabricated in a basic workshop and easy coupled with induction generator [25] for electricity generation. For more simplicity, a centrifugal pump can be used instead of a turbine [3,25] to generate electricity. Furthermore, no extensive training is required to run the pico scheme because end users will be able to install or fix the units [6] on their own by following the operation manual or the manufacturer's guide unit, or by employing the help of their friends who have experienced using a similar technology [6].

*Affordability*. Pico-hydro scheme is one of the most affordable and cost-effective sources of electricity compared to solar, hybrid, wind, or fossil fuel-based options [2]. These are the key drivers that make the pico-hydro scheme more affordable for low-income households:

- Low capital cost. Ongoing research and technology advancements have delivered a higher-quality turbine with affordable price and longer life span (15–20 years) [25,63,94,95] to low-income households [2].
- Less payback period. Pico-hydro technology can be paid back in less than six months [71] if a high-quality pico-turbine fitted the site and the scheme is well managed. As a result, several low-income households will be convinced to buy it [2,71].
- Low annual operation, maintenance, and replacement (O, M, and R) costs. Pico-hydro is a fuel-free scheme (no fuel is needed as in diesel power) and does not require an energy storage system (battery) as in PV or wind. Thus, low annual operation and maintenance costs are guaranteed [2,25,63]. Maintenance work can also be carried out by owners, and available local materials are more than sufficient for this purpose [93]. In comparison, the total replacement cost of the pico-turbine is equivalent to the cost of buying a new one [2,25,63].
- Low electricity cost. Pico-hydro scheme has the lowest tariff among other renewable energy options at about US¢10/KWH to US¢1020/KWH [25,79], which is less than 15% of the cheapest PV solar home system [25].

*Power continuity*. As pico-turbines generate AC, power is thus continuous and on-demand, and standard electrical appliances such as light bulbs, radios, televisions, refrigerators, and food processors can be directly connected [5,25,63]. In addition, pico-hydro is unlike other renewable energy such as wind and PV where the output power constantly varies. Pico-hydro has the lowest output power variation because output power varies gradually from the wet season to dry season and its total output power can be easily predicted [63,95].

*Sharing*. Sharing of pico-hydro scheme in a rural community is a good approach to break up the total cost of the entire scheme. Sharing will reduce the total cost of a pico project, which gives the rural community an opportunity to invest in high-quality and more durable, reliable units [2,25,66]. This benefit is the reason subsidies are not important and have not been adopted in many less developed countries [2]. On the other hand, sharing is sometimes not the natural choice of the community, but is the only solution for them to gain access to electricity as a result of the scarcity of resources.

*Environmental contribution of pico hydro scheme*. Pico-hydro turbine is considered a mature technology [2] because hydropower is one of the oldest known renewable energy to humankind and the first energy to have been used to generate electricity [143]. Besides replacing fossil fuel and fuel wood, which means reducing $CO_2$ emissions [3,99], it also exploits local resources [1], reduces dependence on imported fossil fuel [3,94], and saves forests from destruction and soil erosion [89,128,144,145]. Pico-hydro turbine has no environmental impact in a large hydro scale because a dam is not needed for pico-hydro. Dams can negatively impact the environment in terms of greenhouse gas emissions (due to methane emissions). Dams can also negative affect wildlife habitats, fish migration, water flow, water quality, and conflicts with river-based leisure interests [48,63].

Pico-hydro is also unlike other renewable energy resources because it is a highly efficient technology (70–90%) with the highest renewable energy capacity factor $>50\%$ compared with 10% for solar and 30% for wind [95].

*Generate income and employment*. Electric power can be used to drive equipment such as grain mills, workshop tools, pumps, and other agro-processing equipment [2,3,5,37,89] for the improvement of product quality. Moreover, the availability of light in the evening enables rural residents to work long hours, increase their production, and double their income [2,5]. [94] claimed that, in some cases, rural income will increase up to 700%.

*Social impact*. Pico-hydro has influenced the lives of people in rural areas in many aspects. Those that benefit from it the most are as follows:

- *Women and children*. Women and children are the most prone victims of social injustice, particularly in less developed countries. They have to do hard manual work such as grinding flour, squeezing mustard seeds to extract drops of oil, and walking for long hours to collect and lift heavy wood packages for cooking and lighting [94]. Thus, women and children are the ones that benefit the most from using pico-hydro power.
- *Community*. Involvement of local residents in the installation activities of the pico scheme will raise the sense of ownership of the scheme, and assist them in practicing better management and maintenance of their schemes. The involvement will also nurture goodwill and enhance social ties among community members [25,144]. In addition, pico lighting will promote social gathering and facilitate housekeeping (cooking, cleaning, etc.) [2,5,94,144].

- *Students*. Pico electric lighting is brighter than non-electric lighting (kerosene, resin-soaked kindling, etc.). It can help kids study more efficiently and do their homework at night comfortably [2,5,94,144]. Non-electric lighting, on the other hand, is extremely inefficient and too costly.

*Health impact of pico hydro on the rural community*. Pico-hydro can cut down indoor air pollution, which results from the burning of biomass by low-income households in remote areas for cooking and lighting purposes. Reduced pollutants save people from getting acute and chronic respiratory diseases [5,144]. [144] estimated that up to 150,000 people, mostly women and children, die prematurely each year in some less developed countries as a result of their exposure to indoor hazards from the burning of biomass fuel.

*Increasing rural electrification rate*. Enabling millions of people in remote areas access to electricity because there are several sites of low flow and head in less developed countries, which are adequate for electricity generation for lighting and other small appliances [2].

Although pico-hydro is the most cost-effective option for rural electrification, it is still accompanied by some minor disadvantages such as limitation of hydropower, unavailability of feasible sites, and impossibility of substitution once developed [4,63] because it is seen as a site-specific technology [14,63,95,146] with seasonal flow variations [22,63,147,148]. These may be the precursor and the cause of battles between pico users and fishermen or farmers over the eligibility of the use of water [63], especially when there are dozens of turbines on the stream forming a dam and causing visual impact, as shown in Fig. 12 [12].

Pico-hydro project also requires civil works and special equipment for scheme survey, which are likely to increase the total cost of the scheme [25,95].

In addition, low-quality units which are cheaper, inefficient, unreliable, relatively unsafe, frequently need repairs, have short life spans of less than two years, and lack electronic and mechanical controllers to regulate output voltage and stop water from flowing into the turbine when the unit needs to be shut down may give a negative impression on the use of pico and a bad reputation in the rural electricity market [2,6,15,68]. Blackouts are very annoying news to pico users, especially when it occurs at night because most units are placed far from homes and fixing them in the dark will cause inconvenience [15]. Heavy rainy seasons are likewise inconvenient because end users avoid using pico during heavy rain seasons to prevent floods and prevent the scheme from being washed away [66]. Besides, pico users are constantly worried about their units being stolen when not in use [2,6]. Finally, sharing is likely to generate a spirit of dependency in the community, which will result in less effort for preventive maintenance [93] and complexity in tariff collection. Tariff may be a burden on those with very low income because they may be obliged to pay a fixed monthly fee for their connection. As a result, some customers may not be able to pay their monthly premiums, which will impede the success and continuation of the pico-hydro scheme [5].

**Fig. 12.** Visual impact of Chinese 200 W low head pico hydro units installed on a stream in Vietnam [12].

## 12. Conclusion

To meet the substantial electricity demand worldwide, which is expected to increase by 77% by 2030 [101], and to respond to the needs of rapid population growth for access to electricity and the call from environmental legislation for $CO_2$ reduction [22], the exploitation of renewable energy resources are now essentially for sustainable energy. Pico-hydro has been proven to be the most cost-effective option for the electrification of remote communities because of its affordability, simplicity, low unit cost ($14/200 W), low electricity tariff (US¢10/kWh–US¢20/kWh), power continuity, income generation, no environmental impact, locally manufactured and managed, and easy to install, operate, and maintain. As such, pico-hydro is becoming an attractive prospect in satisfying the basic electricity needs of remote communities [1].

This potential has been observed in many less developed countries who started exploring and using pico for their rural electrification programs, such as the Philippines, India, Sri Lanka, Laos, and Latin America [4]. There is definitely a significant commercial market for pico-hydropower in developing countries [12]. The size of the global pico market has grown and expanded since its development in the south regions of China and the surrounding countries in the late 1980s. Growth rate in the region is estimated to be within 4 million units. However, the actual market size is certainly larger than this number if disused or undeveloped water mill sites and other pico applications such as energy-recovering systems are taken into account. Pico-hydro technology has been developed to the point where the turbine is locally manufactured in developed countries and electricity centralization is no longer obligatory. This development was mainly due to the need for electricity in rural areas, combined with the successful cost-effective approach implementation and recent innovations in pico-hydro technology. This paper is convinced that pico-hydro will offer the most cost-effective option for present and future rural electrification needs.

## References

[1] Bhusal P, Zahnd A, Eloholma M, Halonen L, Bhusal P. Energy efficient innovative lighting and energy supply solutions in developing countries. International Review of Electrical Engineering (I.R.E.E.) 2007;2(5):665670.
[2] Green J, Fuentes M, Rai K, Taylor S. Stimulating the Picohydropower Market for Low-Income Households in Ecuador. Washington, D.C: Energy Sector Management Assistance Program (ESMAP); 2005.
[3] Williams A. Pico hydro for cost-effective lighting. Boiling Point 2007;53: 14–6.
[4] Howey DA. Axial flux permanent magnet generators for pico-hydropower. In: Proceedings of the EWB-UK research conference 2009. Engineers Without Borders UK Royal Academy of Engineering; 2009.
[5] Maher P, Smith N. Pico Hydro for Village Power—A Practical Manual for Schemes up to 5 W in Hilly Areas. Micro Hydro Centre—Nottingham Trent University; 2001.
[6] Paish O, Green J. The pico hydro market in Vietnam. IT Power 2003:1–3.
[7] Taylor S. Bundling Family-Hydro under the CDM in Vietnam and The Philippines; 2004. Available from: 〈http://www.inshp.org〉.

[8] European small Hydropower Association (ESHA). IT power, Small Hydropower for Developing Countries.
[9] Williams AA, Upadhyay DR, Demetriades GM, Smith NPA. Low head pico hydropower: a review of available turbine technologies. In: Sayigh AAM, editor. World renewable energy congress VI. Oxford: Pergamon; 2000. p. 1475–80.
[10] Haidar AMA, Senan MFM, Noman A, Radman T. Utilization of pico hydro generation in domestic and commercial loads. Renewable and Sustainable Energy Reviews 2012;16(1):518–24.
[11] Ho-Yan BP. Tesla turbine for pico hydro applications. Guelph Engineering Journal 2011;4:1–8.
[12] Meier T, Fischer G. Assessment of the Pico and Micro-Hydropower Market in Rwanda; 2011.
[13] IEA, I.E.A., World Energy Outlook 2006. Paris, France, November 2006; 2006. p. 567.
[14] Williams AA, Simpson R. Pico hydro—reducing technical risks for rural electrification. Renewable Energy 2009;34(8):1986–91.
[15] Smits M. Technography of Pico-Hydropower in the Lao PDR. Lao Institute for Renewable Energy LIRE; 2008.
[16] Yüksek O, Kaygusuz K. Small hydropower plants as a new and renewable energy source. Energy Sources, Part B: Economics, Planning and Policy 2006;1(3):279–90.
[17] Green J, Taylor S. CDM Pilot Project to Stimulate the Market for Family Hydro for Low-Income Households. IT Power Ltd.; 2003.
[18] Taylor SDB, Upadhyay D. Sustainable markets for small hydro in developing countries. International Journal on Hydropower and Dams 2005;12(3): 62–6.
[19] Institute of Energy in Vietnam. Hydropower Department Statistics; 1996.
[20] Green J, Taylor S. CDM Pilot Project to Stimulate the Market for Family-Hydro for Low-Income Households. IT Power Ltd.; 2003.
[21] Community Awareness Development Centre CADEC. Micro-Hydro Yearbook of Nepal. Kathmandu: H.M.G. Nepal, Alternative Energy Promotion Centre; 2002.
[22] Williams A, Porter S. Comparison of hydropower options for developing countries with regard to the environmental, social and economic aspects. In: Proceedings of the international conference on renewable energy for developing countries. Nottingham Trent University/Metronet Rail, UK; 2006.
[23] Anup KC, Poudel G, Poudel S, Khadka M. Hydro Home System—an inventory on rural electrification. In: Proceedings of the 2nd international conference on computer and automation engineering (ICCAE), 2010; 2010.
[24] Maher P. Pico Hydro Designs 2001:1–3/8.
[25] Maher P, Smith NPA, Williams AA. Assessment of pico hydro as an option for off-grid electrification in Kenya. Renewable Energy 2003;28(9): 1357–69.
[26] Williamson S. Low head pico hydro off-grid networks, In: Proceedings of the EWB-UK national research & education conference; 2011. p. 33–8.
[27] People Energy & Environment Development Association (PEEDA). Low Head Pico-Hydro Promotion Project, Nepal; 2009. p. 1–3.
[28] Smith NPA, Maher P, Williams AA. Strategies for sustainable and cost-effective village electrification using pico hydro power. In: Sayigh AAM, editor. World Renewable Energy Congress VI. Oxford: Pergamon; 2000 (p. 1490–1495).
[29] Holland R, Perera L, Sanchez T, Wilkinson R. Decentralised rural electrification: the critical success factors experience of Itdg. In: Sayigh AAM, editor. World Renewable Energy Congress VI. Oxford: Pergamon; 2000. p. 1639–44.
[30] Klunne WJ. Sustainable Implementation of Microhydro to Eradicate Poverty in Africa; 2010. p. 1–10.
[31] Hall Douglas G, Cherry Shane J, Reeves Kelly S, Lee Randy D, Carroll Gregory R, Sommers Garold L, et al. Water Energy Resources of the United States with Emphasis on Low Head/Low Power Resources; 2004.
[32] Purohit P. Small hydro power projects under clean development mechanism in India: a preliminary assessment. Energy Policy 2008;36(6):2000–15.
[33] Taylor SDB, Fuentes M, Green J, Rai K. Stimulating the Market for Pico-hydro in Ecuador. IT Power, UK.
[34] Hatch and N.R. Canada, Low Head Hydro Market Assessment; 2008. p. 1-1–10-5.
[35] Penche C. Layman's handbook "on how to develop a small hydro site. 2 ed. DG XVII, European Commision, 200 rue de la Loi, B-1049 Bruselas, Bélgica; 1998.
[36] Waltham Mea. Low Head Micro Hydro Potential: Final Report to ODA under TDR Contract R6482. Intermediate Technology Group, Rugby, UK; 1996.
[37] Maher P, Smith N. The Pico Power Pack: A New Design for Pico Hydro; 1999. p. 7–8.
[38] Maher P. Community Pico Hydro in Sub-Saharan Africa: Case Study 1; 2002. p. 1–3/8.
[39] Singal SK, Saini RP. Analytical approach for cost estimation of low head small hydro power schemes. In: Proceedings of international conference on small hydropower. Sri Lanka; 2007.
[40] Thake J. The Micro-hydro Pelton Turbine Manual: Design, Manufacture and Installation for Small-scale Hydro-Power. UK: ITDG Publishing; 2000.
[41] AEPC/ESAP. Micro-hydro Data of Nepal, 1962-Mid-July 2001. Lalitpur, Nepal: Alternative Energy Promotion Center/Energy Sector Assistance Program; 2002.
[42] Bhattarai EB. Sustainability of Peltric System in Nepal; 2007. 27/04/2010; Available from: 〈http://www.ideaforum.org/mem_show_articles1.php?id=49&PHPSESSID=d885bd777fa33c1fb762307acfb721d1〉.
[43] Gorkhali HG. Improving Livelihood of Rural Mountain People Through Promotion of Pico-Hydro Technologies.
[44] Devon Association for Renewable Energy, Dartmoor Hydropower Survey.
[45] PowerPal. 28/04/2010; Available from: 〈www.powerpal.com〉.
[46] Picasa; 2011. [Cited 2012 5,4]; Available from: 〈https://picasaweb.google.com/lh/photo/5Hf36xUVXEQCrAydhxDQFtMTjNZETYmyPJy0liipFm0〉.
[47] Ampair Energy Ltd. UW100 'picohydro' turbine; 2011. [Cited 2012 5,4]; Available from: 〈http://www.ampair.com〉.
[48] Nachman-Hunt N. Small Hydropower Systems: Energy Efficiency and Renewable Energy Clearinghouse. Other Information: PBD: 5 July 2001; 2001. Medium: ED; Size: vp.
[49] Summit Blue Consulting LLC. Small Hydropower Technology And Market Assessment. Energy Trust of Oregon; 2009.
[50] Orchard B, Klos S. Pumps as turbines for water industry. World Pumps 2009;2009(8):22–3.
[51] Rawal S, Kshirsagar JT. Numerical simulation on a pump operating in a turbine mode. Texas A&M University System, Turbomachinery Laboratory; 2007.
[52] Williams A. Pumps as turbines: a user's guide. 2nd ed. London: ITDG Publishing; 2003.
[53] Arriaga M. Pump as turbine—a pico-hydro alternative in Lao People's Democratic Republic. Renewable Energy 2010;35(5):1109–15.
[54] Derakhshan S, Nourbakhsh A. Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds. Experimental Thermal and Fluid Science 2008;32(3):800–7.
[55] Williams AA. Pumps as turbines for low cost micro hydro power. Renewable Energy 1996;9(1–4 SPEC. ISS):1227–34.
[56] Greacen C. Project report—Huai Kra Thing micro-hydro project. Border Green Energy Team (BGET); 2006.
[57] Jacobson R. Tesla Bladeless Pumps and Turbines 1991.
[58] Anagnostopoulos JS, Papantonis DE. Optimal sizing of a run-of-river small hydropower plant. Energy Conversion and Management 2007;48(10):2663–70.
[59] Thor S-E, Weis-Taylor P. Long-term research and development needs for wind energy for the time frame 2000 to 2020. Wind Energy 2002;5(1):73–5.
[60] International Energy Agency (IEA). Renewable Energy: RD&D Priorities 2006.
[61] Kumar KVNSP, Praveena E, Kishore PV. Isolated pico-hydropower generation using asynchronous generator for power quality improvement. International Journal of Scientific & Engineering Research 2011;2:12.
[62] Van Arkel R, Owen L, Allison S, Tryfonas T, Winter A, Entwistle R, et al. Design and preliminary testing of a novel concept low depth hydropower device. in: OCEANS. vol. 2011. 2011.
[63] Paish O. Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews 2002;6(6):537–56.
[64] Simpson RG, Williams AA. Application of computational fluid dynamics to the design of pico propeller turbines. In: Proceedings of the international conference on renewable energy for developing countries; 2006.
[65] Alexander KV, Giddens EP, Fuller AM. Axial-flow turbines for low head microhydro systems. Renewable Energy 2009;34(1):35–47.
[66] Vongsaly TB, Smits M, Jordan M, Soulineyadeth S. Pico-Hydropower in Xiengkhuang Province. Lao Institute for Renewable Energy (LIRE); 2009.
[67] Rijssenbeek W. Pico Hydro Systems in Vietnam.
[68] Renewable Energy for Sustainable Development Association (RASDALAO). Statistic of the Energy on Grid and Off-grid and Feed in Conditions of the Energy Sector (D1.04). DGS and EuropeAid; 2006.
[69] Smith N, Ranjitkar G. Power distribution, safety and costs, Nepal Case Study-Part two in pico hydro 2000 [p. 3–5].
[70] Enabling Access to Sustainable Energy (EASE), 025 Pico-Hydropower Innovation and Capacity Building Program (Pilot); 2009.
[71] REEEP, R.E.a.E.E.P. 50 Ways To Eliminate Kerosene Lighting. May 2009 25-12-09; Available from: 〈http://www.reeep.org/file_upload/6119_tmpphp-GRHdHc.pdf〉.
[72] Nfah EM, Ngundam JM. Feasibility of pico-hydro and photovoltaic hybrid power systems for remote villages in Cameroon. Renewable Energy 2009;34(6):1445–50.
[73] Otaki K. Vietnam village hydro—a strategic rural development model. Renewable Energy for Development 2003;16(1):1–3.
[74] Watkiss P, Forster D, Woollam R, Laughton M. Decentralised Generation, Independent Analysis of the Potential Role of Small Scale Distributed Generation.
[75] Sopian K, Zaharim A, Ali Y, Nopiah ZM, Razak JAb, Muhammad NS. Optimal operational strategy for hybrid renewable energy system using genetic algorithms. Wseas Transactions On Mathematics 2008;7(4) [April].
[76] Chuenchooklin S. Development of pico-hydropower plant for farming village in upstream watershed, Thailand. In: Prosperity and poverty in a globalized world: challenges for agricultural research. Bonn, Germany; 2006.
[77] Smith N, Ranjitkar G. Installation and performance of the Pico Power Pack, Nepal case study-Part one, In: Pico hydro; 2000. p. 2–4.
[78] Kashyap A. Water Mill Owners to Generate Power. In: Chandigarh Newsline. 2006, 2007: Indian Express Newspapers (Mumbai) Ltd.
[79] Energy Sector Management Assistance Program (ESMAP). Technical and economic assessment of off grid, mini-grid and grid electrification technologies. Washington, DC: The World Bank; 2007.
[80] Promotion of renewable energy. energy efficiency and greenhouse gas abatement (PREGA). Suoi Chum Small Hydropower Plant in Hoa Binh Province; A Pre-Feasibility Study Report by PREGA; Institute of Energy. Vietnam; 2006.

[81] Motorola Inc. Alternatives for Powering Telecommunications Base Stations; 2007, 6.
[82] Pelikan B, Papetti L, Laguna M. Keeping it clean-environmental integration of small hydropower. In: Renewable Energy World; 2006. p. 74–79.
[83] Singh P, Nestmann F. Experimental optimization of a free vortex propeller runner for micro hydro application. Experimental Thermal and Fluid Science 2009;33(6):991–1002.
[84] Zainuddin H, Yahaya MS, Lazi JM, Basar MFM, Ibrahim Z. Design and development of pico-hydro generation system for energy storage using consuming water distributed to houses. World Academy of Science, Engineering and Technology 2009;59:154–9.
[85] Kumar A, Mohanty P, Palit D, Chaurey A. Approach for standardization of off-grid electrification projects. Renewable and Sustainable Energy Reviews 2009;13(8):1946–56.
[86] Dhanapala K, Wijayatunga P. Economic and environmental impact of micro-hydro- and biomass-based electricity generation in the Sri Lanka tea plantation sector. Energy for Sustainable Development 2002;6(1):47–55.
[87] The World Bank Group. Technical and economic assessment of off-grid, mini-grid and grid electrification technologies annexes. World Bank Energy, September 2006; 2006.
[88] Howey DA, Pullen KR. Hydraulic air pumps for low-head hydropower. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2009;223(2):115–25.
[89] Rothkopf G. A Blueprint for Green Energy in the Americas:Washington, DC; 2009. p. 133–196.
[90] Leclerc M. The very low head turbine enters into industrial phase and confirms its extremely low environmental impact. MJ2 Technologies S.A.R.L.
[91] Teodoro S. Key factors for the implementation of successful, standalone village electrification schemes in Peru. UK: Nottingham Trent University; 2007.
[92] Teodoro S. Electricity Services in Remote Rural Communities: the Small Enterprise Model. ITDG Publications; 2006.
[93] Shrestha B, Smith N. Lessons from project implementation and 20 months of operation. Nepal Case Study—Part 3. In: pico hydro; 2001. p. 1.
[94] Craine S, Lawrance W, Irvine-Halliday D. Pico power-lighting lives with LEDs. Journal of Electrical and Electronics Engineering, Australia 2002; 22(3):187–94.
[95] The British Hydropower Association (BHA). A guide to UK mini-hydro developments; 2005.
[96] Kueny JL. Objectives for small hydro technology, Part I. Institut National Polytechnique de Grenoble. p. 2–24.
[97] XE. 1995–2010 22-03-2010; Available from: 〈http://www.xe.com/ucc/convert.cgi?Amount=1&From=USD&To=LAK&image.x=53&image.y=16〉.
[98] Street RL, W.G.Z., V.J.K. Elementary Fluid Mechanics. 7th ed. Cleveland: New York: John Wiley and Sons; 1996.
[99] Sinha SM. Private participation & state policies' in developing small hydro as alternate source of energy in developing countries. In: Proceedings of the international conference on small hydropower. Hydro: Sri Lanka; 2007.
[100] Taylor S, Upadhyay D, Laguna M. Flowing to the east-small hydro in developing countries. Renewable Energy World 2006:126–31.
[101] Energy Information Administration (EIA). International Energy Outlook 2009. Washington, DC; 2009.
[102] Lemaire X. Fee-for-service companies for rural electrification with photovoltaic systems: the case of Zambia. Energy for Sustainable Development 2009;13(1):18–23.
[103] Hwang I-h. Application of photovoltaic systems for rural electrification at remote Islands. Solar Energy Materials and Solar Cells 1997;47(1–4):295–302.
[104] Chakrabarti S, Chakrabarti S. Rural electrification programme with solar energy in remote region—a case study in an island. Energy Policy 2002;30(1):33–42.
[105] Project IS. IE4Sahel—Energy and poverty alleviation in the Sahel Region. In: Intelligent Energy for Sahel (IE4Sahel) Project: Lisbon; May 2006. p. 1–8.
[106] World Bank. Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices: Washington, DC; 2008.
[107] Urban F, Benders RMJ, Moll HC. Energy for rural India. Applied Energy 2009;86(Suppl 1):S47–57.
[108] Visagie E. The supply of clean energy services to the urban and peri-urban poor in South Africa. Energy for Sustainable Development 2008;12(4):14–21.
[109] Bruno GS, Fried L, Hopwood D. Focus on small hydro. Renewable Energy Focus 2008;9(6):54–7.
[110] World Energy Council (WEC). Energy for Tomorrow's World—Acting Now 2000.
[111] Barnes DF, Plas RVD, Floor W. Tackling the rural energy problem in developing countries. In: Finance and Development. International Monetary Fund: Washington, DC; 1997. p. 11–5.
[112] Martinot E, Chaurey A, Lew D, Moreira JR, Wamukonya N. Renewable energy markets in developing countries. Annual Review of Energy and the Environment 2002;27:309–48.
[113] Maher P. Community pico hydro in sub-Saharan Africa/case study two/Thima, Kirinyaga district, Kenya. Micro Hydro Centre, The Nottingham Trent University; 2002 [07/02/02].
[114] International Energy Agency (IEA). World Energy Outlook 2008 Fact Sheet; 2008.
[115] Nfah EM, Ngundam JM, Vandenbergh M, Schmid J. Simulation of off-grid generation options for remote villages in Cameroon. Renewable Energy 2008;33(5):1064–72.
[116] Say TL. Will consumers and industries face another electricity tariff hike? In: The Star Online. Saturday December 5, 2009, 1995–2010 Star Publications (M) Bhd (Co no. 10894-D).
[117] Ali K. Power tariff to go up by 13.5 per cent next month. In: Dawn Newspaper. DAWN Media Group; 2009.
[118] Tugend A. If your appliances are avocado, they probably aren't green in the new york times; 2008.
[119] OECD/IEA. World Energy Outlook 2002. 2nd ed. 2002: LOUIS-JEAN 05003 GAP, France.
[120] HPM T. Contribution des Energies Renouvelables au Développement Durable du Secteur de Electricité: Le Cas du Cameroun. Belgique: Université Catholique de Louvain; 2003.
[121] Mihamle JD. Cameroon lack of electricity: a hostage situation. African News Bulletin—Bulletin d'Information Africaine, Supplement Issue 2002:445.
[122] Nouni MR, Mullick SC, Kandpal TC. Providing electricity access to remote areas in India: an approach towards identifying potential areas for decentralized electricity supply. Renewable and Sustainable Energy Reviews 2008;12(5):1187–220.
[123] Kirubi C, Jacobson A, Kammen DM, Mills A. Community-based electric micro-grids can contribute to rural development: evidence from Kenya. World Development 2009;37(7):1208–21.
[124] Dung TQ, Anisuzzaman M, Kumar S, Bhattacharya SC. Demonstration of multi-purpose battery charging station for rural electrification. Renewable Energy 2003;28(15):2367–78.
[125] Gustavsson M, Ellega˚rd¸ A¨ The impact of solar home systems on rural livelihoods¨ Experiences from the Nyimba Energy Service Company in Zambia¨ Renewable Energy 2004;29(7):1059–72.
[126] Sinha CS, Kandpal TC. Decentralized v grid electricity for rural India: the economic factors. Energy Policy 1991;19(5):441–8.
[127] Green Energy Jobs. Pico Hydro; 2002–2009 [access on 22-11-2009]. Available from: 〈http://www.greenenergyjobs.com/career-guide/hydro-energy-jobs〉.
[128] Hicks C. Small hydropower in China: a new record in world hydropower development. Refocus 2004;5(6):36–40.
[129] Greek Ministry of Development. Athens, Greece. Available from: 〈http://www.ypan.gr〉.
[130] Kaldellis JK. The contribution of small hydro power stations to the electricity generation in Greece: technical and economic considerations. Energy Policy 2007;35(4):2187–96.
[131] Energy Star. Federal tax credits for consumer energy efficiency [2009 2-12-09]; Available from: 〈http://www.energystar.gov/index.cfm?c=tax_credits.tx_index〉.
[132] United Nations Framework Conventionon Climate Change (UNFCCC). Clean Development Mechanism (CDM); 2006 [20–4–2010]; Available from: 〈http://unfccc.int/kyoto_protocol/mechanisms/clean_development_mechanism/items/2718.php〉.
[133] Zhou S, Zhang X, Liu J. The trend of small hydropower development in China. Renewable Energy 2009;34(4):1078–83.
[134] United Nations Framework Conventionon Climate Change (UNFCCC). The Mechanisms under the Kyoto Protocol: Emissions Trading, the Clean Development Mechanism and Joint Implementation; 2006 [20-4-2010]; Available from: 〈http://unfccc.int/kyoto_protocol/mechanisms/items/1673.php〉.
[135] Taylor S. CDM pilot project to stimulate the market for family-hydro for low-income households, IT Power Ltd, UK; Renewable Energy Association of the Philippines (REAP); Vietnam Support Programme for Sustainable Energy Development (VSED) at the Hanoi University of Technology.
[136] Mariyappan J, Taylor S, Church J, Green J. A guide to CDM and family hydro power. IT Power; 2004.
[137] Shafiee S, Topal E. When will fossil fuel reserves be diminished? Energy Policy 2009;37(1):181–9.
[138] Herath S. Small hydropower development in the context of climate change. In: Proceedings of the international conference on small hydropower: Sri Lanka; 2007. p. 1–6.
[139] Energy Recovery Inc. Energy Recovery Devices for Seawater Reverse Osmosis [2010 30-12-2010]; Available from: 〈www.energyrecovery.com〉.
[140] Taylor S. Conversation about pico-hydropower. Basingstoke: IT Power Offices; 2006.
[141] Ogilvie A. Fee-for-sevice pico hydro-model for providing energy to remote, low-income households. In: The 2nd Hydro Power for Today Conference "Policy Stimulating Hydropower Development". International Network on Small Hydropower (IN-SHP): Hangzhou, China; 2006.
[142] ITPower; 2010. Available from: 〈http://www.itpower.co.uk/〉.
[143] Hydropower I [2005 25-06-2010]; Available from: 〈http://www.ieahydro.org〉.
[144] Alex Z, McKay K. Pico-Hydro Power Plant for Elementary Lighting as Part of a Holistic Community Development Project in a Remote and Impoverished Himalayan Village in Nepal; 2007.
[145] Avinash M, K. kumar DISTRIBUTED GENERATION AND ITS SOCIAL IMPACT.
[146] UNEP Division of Technology, I.a.E.E.a.O.U., *Energy Technology Factsheet: Small Scale Hydro (SSH)*.
[147] Basnyat DB. Fundamentals of Small Hydro Power Technologies. UNEP/GEF, REEEP and East African Tea Trade Association (EATTA); 2006.
[148] Johansson TB, Burnham L. Renewable energy: sources for fuels and electricity. Washington D.C: Island Press; 1993.